Transport, Interfaces, and Modeling in Amorphous Silicon Based Solar Cells

S. Dinca, T. Dylla, J. Liang, A. R. Middya, E. A. Schiff, W. Wang, K. Zhu
Department of Physics, Syracuse University
Syracuse, New York 13244-1130

ABSTRACT

We summarize a model for the effects of low carrier mobilities on solar cells, and show how the mobility affects the useful thickness for the absorber layer. We show that predictions based on hole drift-mobility measurements account fairly well for initial efficiencies in amorphous silicon solar cells, and we summarize measurements of hole drift-mobilities for several materials. We discuss light-soaking effects, and in particular we summarize recent measurements of the correlation of the open-circuit voltage with defect density as light-soaking proceeds in a-Si:H.

1. General Introduction

NREL is supporting a research project at Syracuse University with two broad objectives. First, we seek to understand better how amorphous silicon (and related) solar cells work, and thereby to identify the limitations in their conversion efficiency and the opportunities for improving it. In fact, this research is clarifying how all solar cells based on *low-mobility* materials work, and in this summary we shall explain this idea further. Second, we are interested particularly in the *p/i* and *n/i* interfaces of a-Si:H based solar cells. We are currently completing a multi-year project exploring the possibilities of infrared electromodulation spectroscopy of these interfaces; for lack of space, we shall not describe this research in any detail here [1].

2. Why Low-Mobilities Are Important in Solar Cells

Mobilities are defined as the ratio of the drift speed of a charge carrier to the electric field inducing the drift. Mobilities can *directly* affect solar cells that depend on internal electric fields to collect photocarriers, in which case the carrier with the lower mobility is the limiting carrier. For a-Si:H, holes are the limiting carrier.

The reason that low mobilities are important is the buildup of a positive space-charge of drifting holes under solar illumination. This space-charge causes the internal electric field to collapse to zero near the *p/i* interface over some collection width d_C. d_C is roughly the useful limit to the thickness of an absorber layer under illumination.

Fig. 1 illustrates an analytical calculation for the dependence of d_C upon hole mobility for the simplest possible *pin* solar cell. In this model, the *p* and *n* layers are ideal, and the absorbing, intrinsic layer has no defects at all [2]! The figure also illustrates computer calculations* of the output power for thick cells, along with an analytical approximation. The computer and analytical calculations agree best in the low-mobility limit. As the mobility increases, diffusion-assisted collection of photocarriers becomes important; the cross-over occurs at about the same mobility at which the ambipolar diffusion length L_{amb} is equal to d_C.

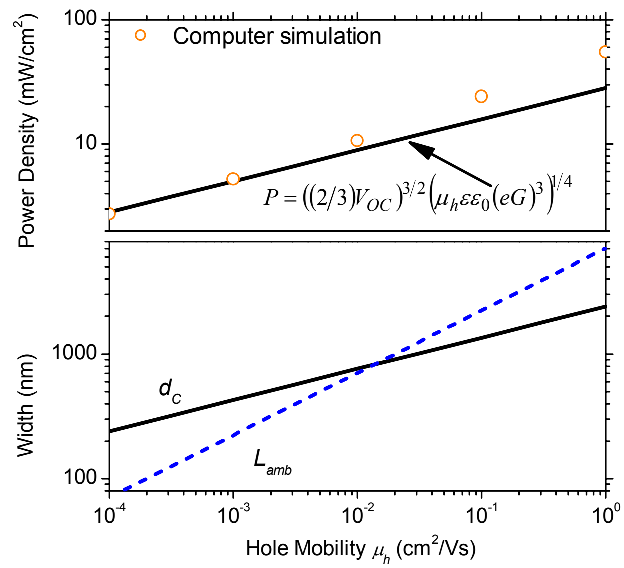

Fig. 1: Dependence of output power density, collection width d_C, and ambipolar diffusion length L_{amb} upon hole mobility for the simplest, defect-free solar cells; the power density was calculated for thick cells. Photogeneration rate $G = 10^{21}$ cm^{-3}s^{-1}; recombination coefficient $b_R = 10^{-10}$ cm^{3}s^{-1}.

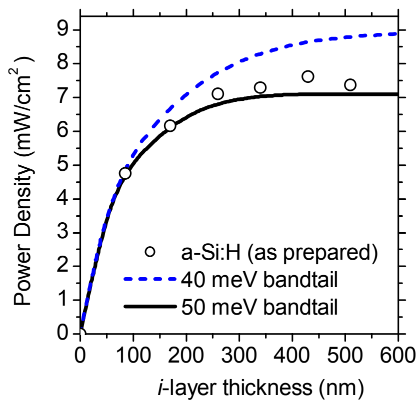

Fig. 2: Symbols show the dependence of initial output power for a thickness series of a-Si:H *pin* solar cells. The solid and dashed lines are computer calculations based only on hole mobility measurements (and neglecting defects). The curve labeled “50 meV” uses parameters consistent with experimental hole drift-mobility measurements on similar a-Si:H materials; the curve labeled “40 meV” indicates the improvement associated with a substantially increased hole drift mobility.

* We used the ®AMPS PC program developed at Pennsylvania State University.

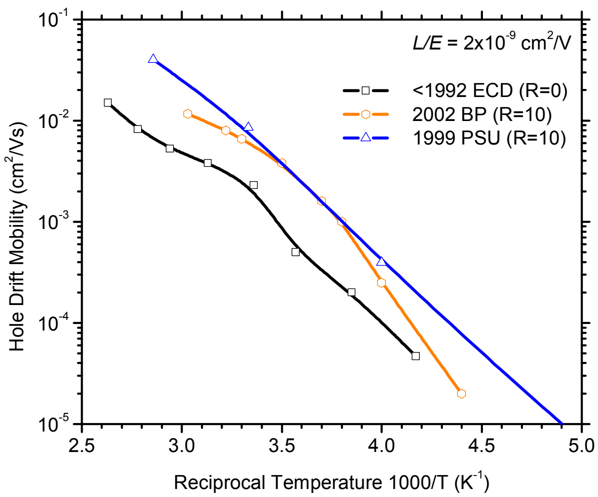

Fig. 3: Hole drift-mobilities measured for varying temperatures in 3 samples of a-Si:H. The parameter R is the hydrogen/silane dilution ratio. ECD: Energy Conversion Devices, Inc.; BP: BP Solar, Inc.. PSU: Pennsylvania State University.

These same principles may also be applied to amorphous silicon, for which the low mobilities measured for holes are ascribed to the effects of valence bandtail traps. In Fig. 2 we show the dependence of the initial output power density under solar illumination for a thickness series of a-Si:H solar cells (taken from a review paper by Guha [3]). The solid line indicates computer calculations that used parameters based on hole mobility measurements on comparable intrinsic layers, and that neglected the effects of deep levels such as dangling bonds. The agreement is rather good.

Although it is not shown here, light-soaking reduces the output power for thicker cells by about 30%. This effect is normally modeled by including deep levels, whose density increases with light-soaking. We discuss our own experiments with light-soaking shortly.

3. Hole Drift Mobilities

The close relationship of hole drift-mobility and conversion efficiency that is implicit in Fig. 2 needs to be elaborated. We are measuring hole drift mobilities in cells with significantly varying properties to see how well the measurements predict the cell properties, and to understand how hole mobilities depend upon deposition parameters. For example, we are presently working to explain the significant increase in hole drift mobilities (about fourfold) that has been achieved by device makers in the last decade. Some of the related measurements are presented in Fig. 3, which shows the hole drift-mobility† as a function of temperature for three samples. The lowest curve was measured about ten years ago [4], and is consistent with drift-mobilities reported by several groups for a-Si:H during the 1980's. Drift mobilities in materials prepared more recently are plainly higher. We believe the increase is due to the use of hydrogen dilution in plasma deposition, but this has not yet been proven.

In addition to this work with a-Si:H, we are also measuring hole drift mobilities in microcrystalline Si solar cells made at Forschungszentrum Jülich. Preliminary results indicate a mobility of about 0.5 cm^2/Vs. It is interesting to look up the corresponding value for the collection width d_C in Fig. 1, which is about 2000 nm. Optimized cells [5] generally do have about this thickness, although we have neglected some important details such as diffusion-assisted collection and the differences in photogeneration rates for a-Si:H and microcrystalline Si.

4. Light-Soaking

Light-soaking is generally perceived as completely changing the optoelectronic properties of a-Si:H, and it is true that the defect density increases very substantially. However, optoelectronic properties measured *under solar illumination* conditions are not so dramatically affected. For example, in Fig. 4 we show some of our recent measurements of the open-circuit voltage in an a-Si:H solar cell as light-soaking progresses; the photocurrent in the cell measured in the infrared was used to monitor the increase in the defect density. The figure suggests that the initial value for V_{OC} is about 0.015 V smaller than the "zero-defects" state; we haven't measured the light-soaking process at sufficiently long times to establish the final state, but .would estimate a decline of about 0.05 at 50 C based on United Solar's light-soaking experiments. The relative effect of light-soaking on V_{OC} measured at low intensity is much larger [6].

The fact that light-soaking affects the high-intensity

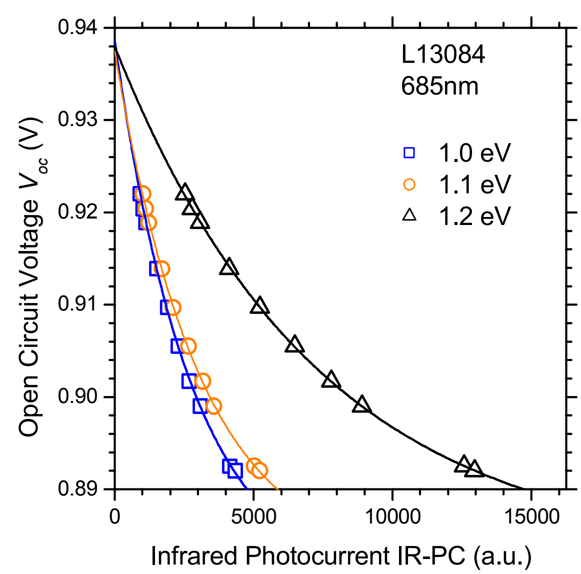

Fig. 4: Correlation of the open-circuit voltage with the infrared photocurrent at the indicated photon energies for an a-Si:H solar cell (United Solar Systems Corp.). The different points indicate differing light-soaking states. The photocurrent indicates the midgap optical absorption, and is generally taken to be proportional to the defect density. V_{OC} was measured at 685 nm and a reverse-biased photocurrent of 1.6 mA/cm^2.

† Comparison of hole drift-mobilities in different materials must be done for a specific ratio L/E of the sample thickness L and the electric field E; the dependence of the drift-mobility upon L/E is an aspect of the "dispersion" effect.

optoelectronic properties (such as V_{OC}) only modestly suggests to us that the decline in these properties is "self-limiting." For example, the "zero-defects" limit for V_{OC} is determined by recombination of photogenerated electrons with holes trapped in the valence bandtail. If this recombination process is the mechanism that spawns defects, then - as more defects are generated - recombination through the defects begins to replace the bandtail process – and thus slows down the rate of defect formation until a steady-state is achieved. The ideas are similar to those proposed long by Stutzmann, Jackson, and Tsai, by Redfield, and by others, but needs to be further elaborated to exploit V_{OC} data.

5. Conclusions

Our research indicates that hole drift mobility measurements are essential to understanding the initial conversion efficiency of a-Si:H and microcrystalline solar cells. We have undertaken a series of measurements of hole drift-mobilities in a-Si:H and microcrystalline Si to improve our understanding of hole properties. We do not yet know the relationship of the initial properties to the degraded properties of cells following extended light-soaking. The degradation in the optoelectronic properties of cells under full illumination is not a dramatic one, amounting to a loss of about 30% in conversion efficiency and about 5% in open-circuit voltage. We speculate that this "self-limiting" behavior reflects a causal link between the initial and light-soaked states. Hydrogen-dilution experiments also suggest this link: both the hole drift-mobility and the stability of a-Si:H can be improved by hydrogen-dilution. We plan more conclusive experiments on the dilution effect, as well as additional experiments to test and refine model parameters describing the "zero-defects" state of a-Si:H solar cells.

Acknowledments

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